Experimental Investigations of the So-called

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Izvestiya Akademii Nauk SSSR, Seriya Fizicheskaya,
Volume XII, No 3 (May/June 1948), pages 267-287.

Moscow: May/June 1948.

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EXPERIMENTAL RESEARCH ON THE SO-CALLED ANISOTROPY EFFECT OF THE IONOSPHERE

Ya. L. Al'pert

1. INTRODUCTION

In the preceding article (1) we indicated that in the course of experimental studies of the ionosphere we discovered a certain new phenomenon called "Effect of Anisotropy of the Ionosphere" (2). In order to explain this phenomenon we developed a theory in the above mentioned article. Complex and cumbersome calculations were needed to transform the results of theoretical findings into numerical values and graphs and to obtain a clear picture.

There were also many difficulties in the experimental part of the work.

As far back as 1945, while experimenting with the equipment described below I discovered that the values of the azimuths of the common and uncommon impulses reflected from the ionosphere are considerably different in magnitude. Moreover, in cases when both signals are "mixed" (because of the small difference between their times of group retardation), the direction of this signal is more often than not very unstable and indefinite. The separate signals, on the other hand, have entirely definite values for their directions and certain of their transmutations, which are observed experimentally, may easily be detected by measurements.

In order to explain the physical nature of the observed phenomenon, we suggested that it is provoked by anisotropy of the ionosphere, and more precisely by the fact that the propagation trajectories of the so-called common and uncommon waves deviate from the plane of descent much as light deviates in a crystal from the plane of descent when its optical axis is not collinear with it. The explanation of this phenomenon, simply stated in such a general form, could, of course, not be deemed satisfactory. What was basically interesting in this case was the quantitative side of the effect. Later, as should be noted, after completion of almost all experiments, we made the corresponding calculations and all these questions were clarified.

The study of this phenomenon required a series of experiments establishing the relation between this effect and the angle between the horizontal component of the magnetic field of the earth, which in the given case is analogous to the optical axis, and the direction of wave propagation. The setting up of these experiments turned out to be rather ponderous and complicated.

Besides, it was indispensable to check thoroughly the methodology of measurements and the equipment. The fact is that the direction finding of radio waves reflected from the ionosphere is, as we know, a difficult job because of the elliptical condition of their polarization. The Edcock direction finder which we used usually is free from polarization errors. Engineering practice shows, however, that at comparatively small distances from the radiator (where we made the measurements), even this type of direction finder is subject to polarization errors. Therefore, in order to control the equipment, we were forced to make the series of measurements described below.

With this aim in mind, together with various checks which we made on the spot, we also experimented with a plane especially flying around the region where the receiving equipment was located. Control experiments showed that the conditions in which the experiments described were conducted insured the necessary reliability of the measurements.

Another question arose, however. Why does practice with these direction finders indicate their unreliability in work at comparatively close range from the radiator? An analysis of this problem showed that the reason, more often than not, is to be found not in the equipment, but in the fact that one usually has to do with a "mixed" wave consisting of two elliptical polarized waves having different revolution signs. In our case the bearing also became indefinite when both signals mixed together. It became stable with a deep minimum when the common and uncommon signals "untangled" and when the error of the bearing was revealed as lying in the nature of the phenomenon itself rather than in the limited possibilities of the equipment. In fact the possibilities of using the equipment are better than is thought. Moreover we checked by calculation the character of the bearing in the case of presence of polarization errors in the equipment. This calculation also confirmed the reliability of the measurements made.

In this work, we describe the results of experiments conducted, the experimental methodology and equipment. We also discuss the data obtained.

2. DESCRIPTION OF EQUIPMENT AND OF THE EXPERIMENTAL METHODOLOGY OF OBSERVATION

The impulse method of research was used for the experiments. The receiving and transmitting equipment was set up in two different installations.

The main diagram of the transmitting device is shown in Figure 1 (3). The frequency diapason spanned by the transmitter formed 1.1 $\div$ 12 MHz; the frequency of the impulse modulator 50 Hz (alternate current grid); impulse duration was $\sim 0.5 \cdot 10^{-4}$ seconds, while the transmitter's radiation power was ~ 0.5 kW.

The main diagram of the receiving device is shown in Figure 2. We see that the receiving device is nothing but an Edcock direction finder plus a cathode oscillometer and a time tap. The antenna consisted of four vertical rods 00, each one of which was divided into two electrically isolated halves connected to the feeder cables which went to the goniometer G. The antennae were set up on supports insulated from the earth. One pair of antennae was disposed in a NS direction, the other in an EW direction. The receiver and other auxiliary devices were housed in a wooden booth that also received the antennae feeder cables. Besides, we also had a vertical antenna for compensating the so-called "antenna" effect. The discharge of the receiver intermediate frequency was sent to the amplifier (to the vertical pair of leaves) of the cathode oscillometer equipped with a linear time recorder. Time recordings of the impulse kind with a frequency of 2500 Hz were connected with the modulator of the oscillometer. The time recordings were obtained from an RC-generator synchronized by an alternate current grid. To make it possible to regulate the position of the received impulses along the time scale, the grid tension which synchronized the time recordings, was connected to an RC-generator by means of alternate current phase rotator.

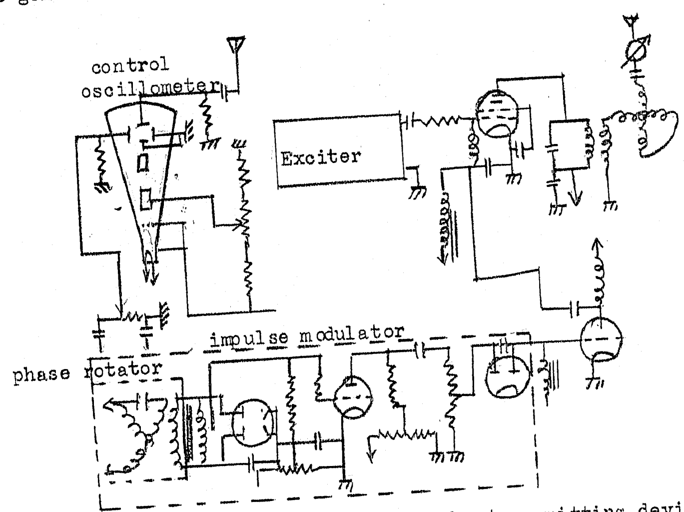

Figure 1. Basic schematic Diagram of the transmitting device

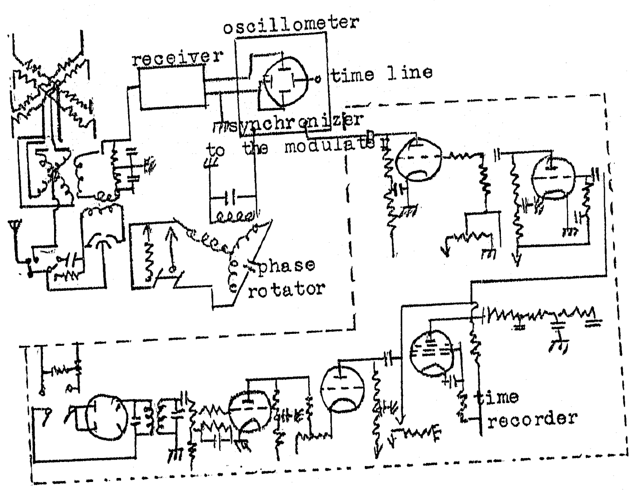

Figure 2. Basic Schematic Diagram of the receiving device

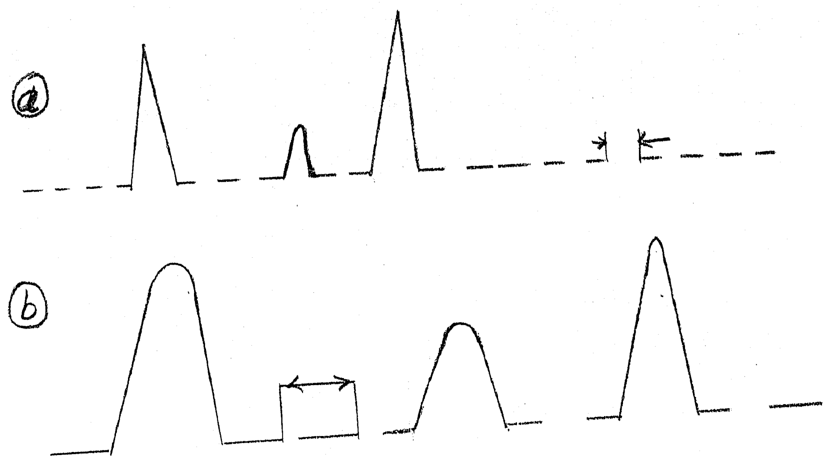

Figure 3. Common Oscillogram: (a) compressed oscillogram, (b) extended oscillogram

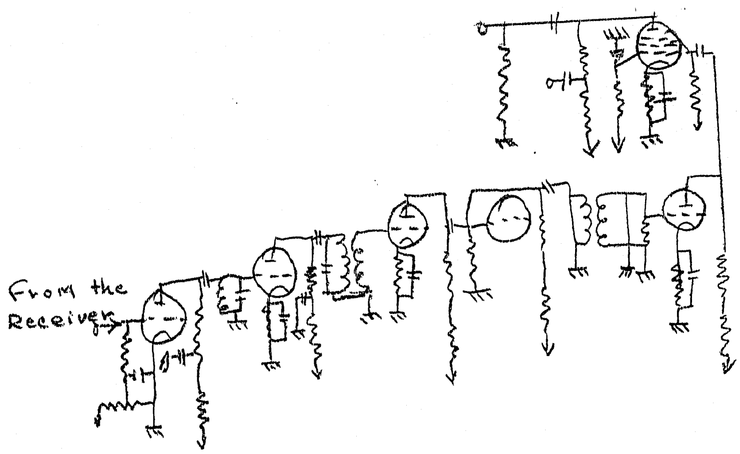

Figure 4. Diagram of the device for the synchronization of the time line with the help of the received impulses.

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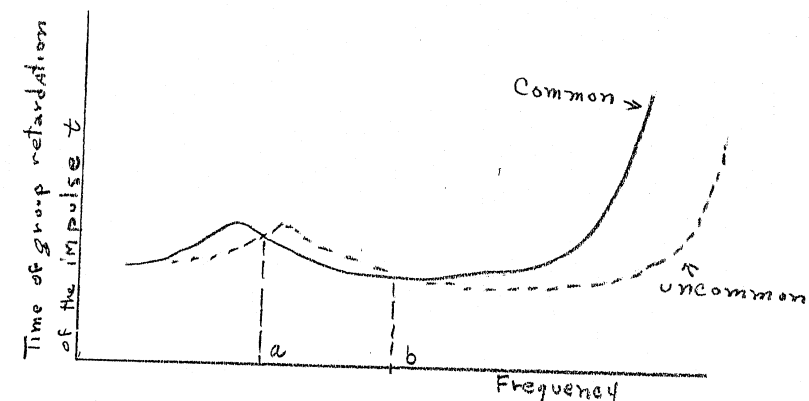

Figure 5. The relationship between times of group retardation of common and uncommon signals and frequency.

Figure (3) shows a common oscillogram. One should note that the experiments were conducted under such conditions that the level of the signals used more often than not covered external interferences to a significant degree. The picture on the oscillograph was clear and the measurements were conducted with sureness. When, for one reason or another, the relative level of the signals studied weakened, the experiments were discontinued. The receiver was powered by an accumulator, while all the additional devices were powered by the alternate current grid.

An alternate current MOGES type grid was used in all experiments, both in the transmitting and in the receiving devices. Therefore the synchronization between the frequency of the impulses transmitted and the time recorder was automatic. However, for the synchronization of the time line with the help of received impulses, we also built and tested the device the circuit of which is shown in Figure 4.

[The received impulses were sent to a tube generator with a frequency of 50 Hz which they synchronized. In order to synchronize the time line the output of this generator was sent to the oscillograph. The tests of this circuit yielded positive results.] During all the experiments, the receiving installation was located at Krasnaya Pakhra on the NIIZM territory. [I take this occasion to express my sincere thanks to the director of N. V. Pushkov, for the help given us in our work.] The transmitting installation was located at various points in the Moscow region.

The observation method consisted of the following: during almost every session of measurements, lasting from half an hour to an hour, the frequency of the transmitting apparatus was changed intermittently so that the measurements began at a frequency at which the reflextion took place in the lower part of the ionosphere F layer where the splitting of the signal is not commonly observed. After that the frequency was increased up to the critical frequency, first of the F_1 layer and then of the F_2 layer.

The splitting of the signal was gradually noticed, first in the region of the critical frequency of the F_1 layer (in the summer), and then also in that of the F_2 layer. When possible the session was terminated after the gradual disappearance first of the common and then of the uncommon signals. Such measuring sessions with a comparatively slow marking of height and frequency characteristics were repeated several times during each experiment.

The experiments were conducted fairly regularly during all the seasons of the year, mostly in the day time (from sunup to sundown). This time was the most free from interference by distant radio stations.

At each experiment we registered, for each of the frequencies used, the times of the group retardation of each one of the reflected signals and the direction of their arrival (the value of their azimuths).

Since the receiving station was located near the automatic ionosphereric station of the NIIZM, it was possible to compare the values of the critical frequencies of the F_1 and F_2 layers determined by our experiments with the data of this station. This control was important only in the initial stage of our experiments when the more complicated height-frequency characteristics of the type shown in Figure 5 were want to happen. These are often observed in the summer. These characteristics have this peculiarity: in a certain frequency interval (ab in the figure), the doublet of the signals has a time sequence opposite to the usual one, i.e. the uncommon signal has a higher retardation than the common one. It is often impossible to distinguish the common signal from the uncommon without making measurements in the uninterrupted range of frequencies. However, as the experiments have shown, in view of the possibility of distinguishing the common signal from the uncommon according to the direction of their arrival no discrepancies were observed between our measurements and the data of this station. [One must note that a significant number of measurements was conducted during the winter at temperatures of -15 ÷ -20 degrees centigrade. We began the measurements early in the morning,

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upon arriving from Moscow, often even in the night, without a previous check of the equipment which remained in the booth all year long. Even so the equipment functioned flawlessly.]

3. CONTROL EXPERIMENTS TO TEST THE EQUIPMENT

Before we go on to describe the results of all the experiments, let us deal briefly with a certain part of the control measurements made to check the equipment. The basic aim of this check was to determine whether the horizontal component E_x of the electromagnetic field of the reflected wave had any influence on the antenna system under the experimental conditions. It is known that a correct direction finding can be done only with the vertical component of the field E_z alone. In other cases the antenna system is not free from polarization errors and it is impossible to determine the true arrival direction of the wave front to the receiving point. In fact, under such conditions, the position of the principal axes of the ellipses of the wave reflected from the ionosphere is often determined. [Let us note that Edcock's antenna system is in a certain sense analogous to two nicols which allow to obscure completely the elliptically polarized light.

Why does such a danger arise if the antenna system is sufficiently well constructed and its horizontal parts (feeders) are controlled and sufficiently symmetrical? This danger arises during measurements at close range because in these cases the angle between the normal of the reflected wave front and the surface of the earth is very large (near to 90 degrees) and $E_x \gg E_z$.

For example, the ratio $\frac{E_z}{E_x}$ oscillated in our experiments

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within limits of $\frac{1}{5} \div \frac{1}{15}$, depending on the distance between the transmitting and the receiving stations. The system of feeders may fully assure the compensation of the horizontal component of such a value. It is quite understandable, however, that in order to keep E_x from affecting the results of the measurements it is indispensable that it be compensated in the system by a value of a higher order than the ratio $\frac{E_z}{E_x}$ cited above. Moreover, we have many indications that under such conditions it is very difficult to operate even with Edcock's direction finders.

The effect of E_x on the results of the measurements was determined by three methods:

(1) With the help of certain manipulations of the equipment.

(2) By means of experiments with an airplane.

(3) And finally by an indirect way -- comparison of various experimental data, and also of basic results of experiments with the results of the calculations of the values of expected effects during reception of E_x. The data, referring to the last point, will be given in the following section.

The following control experiments were made with the equipment. One could have supposed that as a whole, the system of feeders functions as a system of horizontal antennae receiving a revolving elliptical field created by the reflected waves at the point of reception. In order to check this, we cut the feeders off (electrically) from the vertical antennae and the reception was made with the feeder system alone. [The apparent resistance of the whole antenna system had to change thereby, however the tuning of the system was possible.] After disconnecting the feeders, the reception of the impulses being studied ceased completely and only with a maximal gunning of the receiving set a very weak reflected impulse, devoid of a definite direction, appeared every once in a while on the oscillograph. We repeated these measurements several times in a wide range of frequencies under conditions when strong reflections from the ionosphere were present. We connected the feeders back to the antennae in such a way that we could take measurements with each one of them separately. Each time the goniometer reacted in the direction corresponding only to each one of the antennae, and the usual picture on the direction finder was obtained only when all the antennae were connected.

Moreover we supposed that any assymetry is possible in the antenna and goniometer systems. Such asymmetries can show up when the antennae are circularly connected to the same arms of the goniometer and also when the upper and lower halves of the antenna or of the goniometer are cross-connected. The corresponding manipulations were carried out in all the possible combinations and did not disclose the presence of any abnormalities.

The airplane experiment was set up as follows. A plane equipped with a radio station functioning in the frequency range which interested us flew over the receiving point in several radial directions, beginning at 15-20 kilometers from it. The pilot directed the plane over determinate landmarks and also over the receiving point. Special gas jets were lit near the receiving point upon instructions from the plane. Fairly convenient flight directions were chosen for the plane and each time it flew with good precision over the receiving point. Moreover the plane made several circles of small radius and as high as possible right over the receiving point. During these flights reception and direction finding of the plane radio station were made continuously. The flights were organized to determine the angles with the Z axis and directions of arrival of the wave from the plane under which it is impossible to get a direction finding. During this experiment we obtained the following results. The trajectory of the plane flight over the receiving point, obtained by means of radio direction finding and compared with time signals broadcast from the plane, is shown in Figure 6. The same figure shows one of the circles described by the plane over the receiving point. Because of cloudiness the plane could fly no higher than 1000 $\div$ 1200 meters. During the whole experiment the bearing of the plane was never lost, even at the moment when it flew over the station or circled above it. Naturally it never flew exactly over the station. According to observers on the plane and on the ground it flew at a distance of $\sim 50 \div 100$ meters on each side of the apparatus. As the plane approached the receiving point, the ratio between the vertical and the horizontal components of the field $\frac{E_z}{E_x}$ of the plane radio station diminished constantly. Calculations show that during the most favorable moments, when the plane circled or flew over the station, $\frac{E_z}{E_x}$ changed within limits of $\frac{1}{20} \div \frac{1}{4}$. In all these cases the position of the plane was determined correctly within the bounds of measuring precision. [Naturally, we do not mention here certain details of the experiments.]

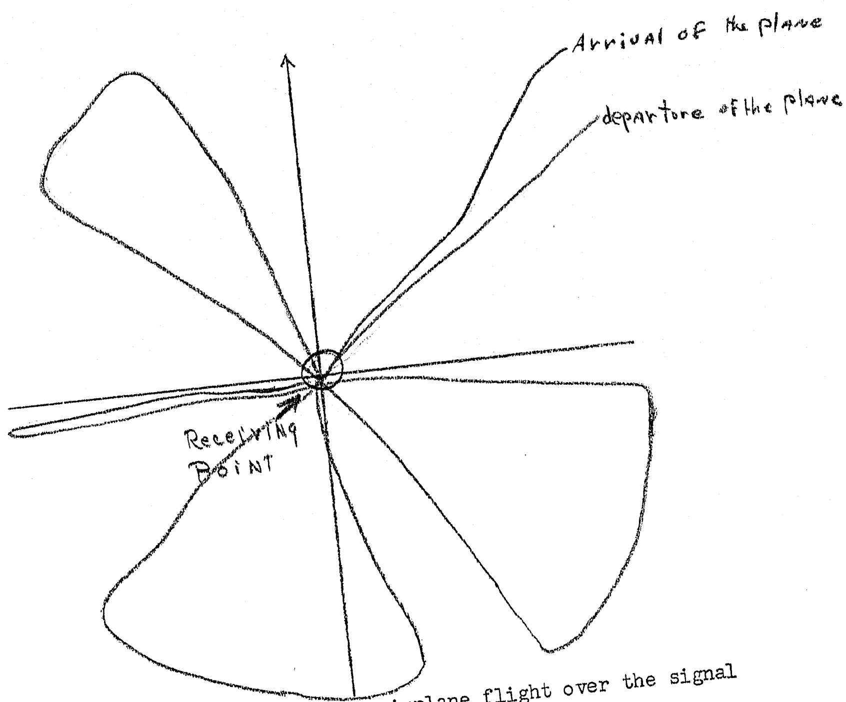

Figure 6. Trajectory of an airplane flight over the signal receiving point for the control of the effect of the horizontal component E of the electromagnetic field on the antenna of the direction finder.

Besides the indicated measurements we also conducted experiments with an auxiliary generator which was transported around the direction finder. We compared the optical and radio bearings. We also experienced with distant radio stations and the results were compared with the actual azimuth. These measurements showed that within the limits of essential precision the direction finding was correct.

We also checked to see whether there were any substantial errors provoked by re-radiation of surrounding objects. With this in view we moved the whole equipment to another site within the boundaries of the same territory but at a considerable distance from the initial point and where it had a different disposition in relation to surrounding objects and where the re-radiation, should it have any influence, would bear a different character. After a few hours the experiment was continued on the new site. The new test gave the same values for the earth impulse and for those reflected from the ionosphere.

We must note that the effects studied (see the following section) are significant in their magnitude and that we do not consider errors of the order of 2 $\div$ 3° as important.

4. RESULTS OF THE EXPERIMENTS AND THEIR DISCUSSION

We indicated above that in the experiments here described, together with measurements of the time of group retardation of various signals reflected from the ionosphere, we also registered the values of their azimuths. Most interesting in relation to the effect which we are here studying is the analysis of the data which characterize the arrival to the receiving point of signals reflected from the region F, especially in the presence of a signal doublet provoked by a double ray refraction of the ionosphere. However, it may be useful to consider briefly the characteristics of the azimuth values of other reflected signals. In a certain measure these data are essential for a full analysis of the phenomenon which interests us and of its consequences.

Characteristic of Azimuth Signals Reflected from the E Layer

It is well known that the E layer is a thin region. Therefore, upon studying the impulses reflected from it we seldom observe a double refraction because the common and uncommon signals in it diverge very little. We obtained a series of data, however, which still indicate that the effect we are studying may be observed even in the E layer. This is interesting also because it confirms the electronic nature of the E layer and every new experimental proof of this fact up to the present time has been of great interest.

In our experiments we observed only a few reflections from the regular E layer. This was caused by the frequency range we chose, which usually was higher than the critical frequency of the layer. A few experiments, however, were conducted with frequencies near and below the critical frequency of the E layer. We observed a single reflected signal from the E layer whose azimuth hardly ever coincided with the azimuth of the earth signal, i.e. with the true direction.

All the data gathered for the E layer were obtained while the transmitting installation was located in Moscow, at a distance of 38 kilometers from the receiving point, (see Table). The value of the azimuth of the earth signal, always coinciding with its true value, is equal to +27 degrees. [In this article angles are always measured clockwise, beginning from the Northerly direction.] The azimuth of the horizontal component of the magnetic vector, i.e. the inclination of the earth magnetic field was under our experimental conditions equal to +7 degrees, while the azimuth of the signal reflected from the E layer oscillated around an average value of $\sim$350 degrees (-10 degrees), i.e. formed with the true direction an angle $\measuredangle_e \approx -37$ degrees. This fact is very characteristic since we will see later on that for this point of observation the uncommon signal reflected from the E layer, had an average value of

$\alpha_e \approx -53$ degrees (the averaging was drawn from a few tens of measurements, and the maximum oscillating amplitude of the value α_e was at all times $\sim$10 degrees, see below). From these isolated measurements alone we get the impression that apparently in this case we were dealing with an uncommon signal of the E layer.

Characteristic of the Signal Azimuths Reflected from the E_{spor} Layer

A large number of reflections are observed from the sporadic E_{spor} layer. An analysis of these has shown the following.

(1) In the presence of stable reflections from E_{spor} in a sufficiently wide range of frequencies the azimuth of reflected signals on the lower limit of frequencies had a value which from test to test changed within the limits of +10 ÷ +25 degrees. The individual measurements were stable within the precision limits of the calculation (±2 — 3 degrees). The azimuth of the reflected signal on the upper limit of frequencies had values of 340 ÷ 355 degrees. Figure 7 shows a certain part of the measured values of signal azimuths reflected from the E_{spor} layer, corresponding to the smallest (f_{min}) and the largest (f_{max}) frequency values under which these reflections were observed. The thin lines connect the points referring to one and the same experiment.

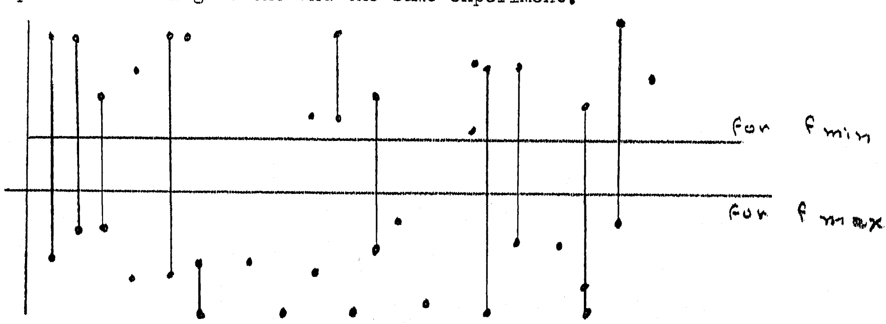

Figure 7. Values of the azimuths of signals reflected from E_{spor} for f_{min} and f_{max}. The thin lines connect the points referring to one and the same experiment.

(2) In cases where only accidental reflections were had from E_{spor} their aximuths mostly had stable values in the interval 340 ÷ 350 degrees (-10 ÷ -20 degrees).

(3) Fairly often the azimuth of the impulses from E_{spor} was unstable and changed so fast that even after a few seconds the measurements became incorrect. This happened mostly in cases where an intensive E_{spor} was observed (the signals were reflected from it in a large range of frequencies, up to very high ones). The fast oscillations of the signal azimuth occurred in the interval of 350 ÷ 10 degrees, i.e. with an amplitude of 20 degrees. However, often the oscillation amplitude reached 40 degrees and often the bearing revolved -- the value of the signal azimuth changed rapidly within limits of 360 degrees and in general became indefinite.

In relation to the data for E_{spor} we may note the following facts: when stable values of bearings were observed (as shown in sections 1 and 2), we apparently were dealing respectively with common and uncommon impulses reflected from E_{spor}. For the uncommon impulse we got values of $\alpha \approx -32 \div 47$-degrees ; while for the common impulse we got values of $\alpha_o \approx 2 \div 17$ degrees. This is in good accord with the data for the F layer given below, (see table).

On the other hand, when we observed instability in the azimuth values or a revolution of the signal bearing, we apparently received a "mixed" signal consisting of a common and an uncommon impulse. Depending on the relation between the amplitudes of the common and uncommon signals and on the difference of their phases, the value of the mixed signal bearing must vary, for each one of them separately has different (and stable) azimuth values. As a result of their combination there occurs an interference in direction. From the following data we will see that such a peculiar directional fading is also observed in other cases and in practice may often be the cause of the bearing's instability.

<u>Characteristic of Signals Reflected from the F Layer Directional Fading</u>

The study of impulses reflected from the F layer were made with the transmitter in different positions. First let us mention their general characteristics taken from the analysis of a large quantity of obtained data. These characteristics are as follows:

(1) With frequencies sufficiently removed from the critical frequencies both of the F_1 and F_2 layer and while observing just one reflected signal, the latter under certain conditions [Depending on the time of year, time of day, etc.] had a stable bearing value corresponding to the value of the azimuth of the common signal at that point (see table). Often, however, especially in the case of a frequency increase, the bearing became unstable, rapidly and amply oscillated, sometimes revolved and became generally indefinite, especially upon approaching those frequencies that brought on a signal doublet.

(2) With the splitting of the signal into two (common and uncommon), which first becomes visible by the splitting and widening of the impulse apex, it became possible to take the bearing of both signals. Both of them had a stable bearing value with a

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deep minimum. Certain oscillations of the bearings of both signals were observed fairly often, but not very strongly. The individual measurements were fairly accurate and were often repeated during a long span of time within the limits of measurement accuracy. The corresponding data on the azimuths of various impulses, obtained with various positions of the transmitter, are given below (see table). The oscillating ranges of azimuthal measurements in the various experiments are seen in Figure 8 where we show a part of the measurements for the time when the transmitter was located in Moscow. One must note that the figure shows individual measurements corresponding to experiments made with long intervals in time (several months). The data on the figure testifies to the good continuity of the measurements.

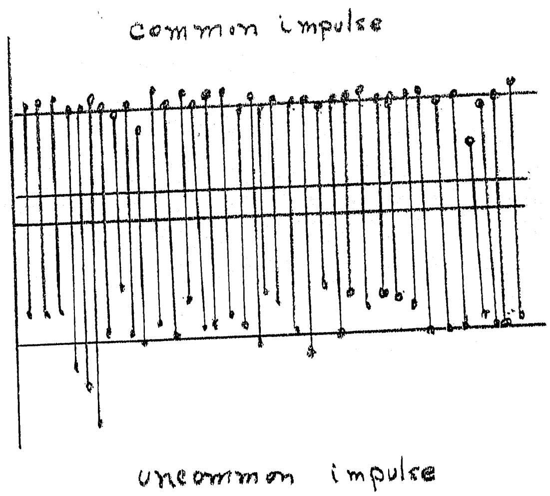

Figure 8. Oscillating ranges of individual measurements of azimuthal values for common and uncommon impulses reflected from the F layer obtained in various experiments.

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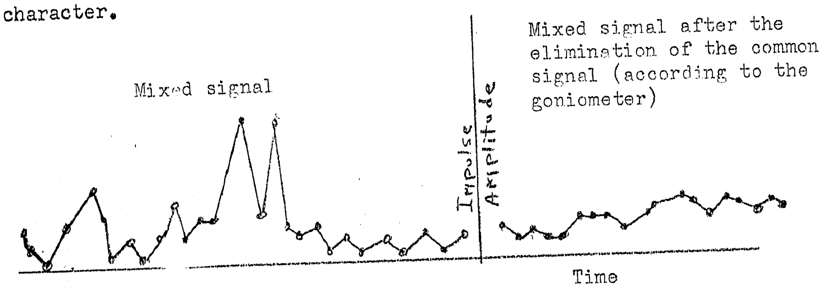
(3) The stability of observation of the azimuthal values of the common and uncommon signals for each point made it possible to distinguish the signals of different types of polarization. This means that in the cases when (because of the influence of the F_1 layer) the common signal had a lower time of group retardation than the uncommon signal, one could recognize these signals from the corresponding bearing values. In spite of the fact that in experiments with fixed frequencies one does not always know at the time of measurement in what region of the altitude -- frequency characteristic the measuring is being conducted, the following comparison of these data with the NIIZM ionosphere characteristic never led to any discrepancies. Similarly, when in certain cases because of a strong selective absorption in the lower layers one of the signals of the doublet was absent (either the common or the uncommon one) it was possible, by the bearing values to determine which one of these signals had been received and these findings always proved correct.

The data on the conduct of various signals which we have given above show that the signal reflected from the F layer had a different nature in different cases. When the azimuthal value of the signal was stable and coincided with the azimuthal value of the common signal at that point, apparently it actually was the common signal. The presence of only one signal could derive from the fact that in these cases the uncommon signal had a very low intensity because of strong absorption. Much more seldom we observed the opposite, when the single signal was only uncommon. This could derive from the selective absorption of the common signal. In these cases the signal azimuth had a corresponding value. However, more often than not, the signal was of a mixed nature, and was made up of two impulses (common and uncommon). This led to the appearance of the above mentioned directional fading and had to lead also to an increase in amplitude fading. For such cases we tried the following experiments: at intervals of 20-30 seconds we registered the amplitude of the mixed signal, first with an arbitrary position of the goniometer and then with a position of the goniometer corresponding to the minimum either of the common or the uncommong signal. In the latter position the goniometer was not supposed to receive the corresponding signal and the amplitude fading was supposed to change its character.



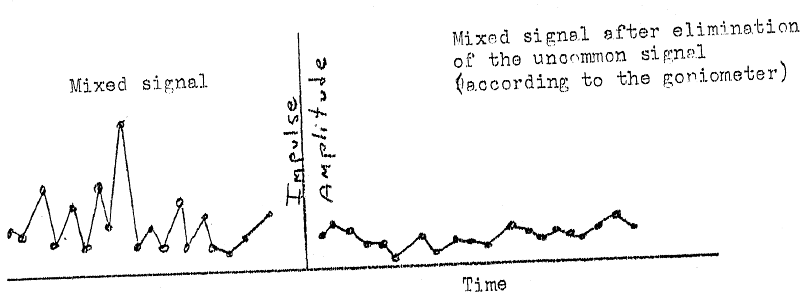


Figure 9. Results of the study of "mixed" signal fading

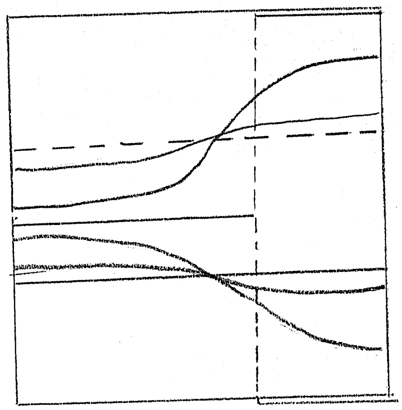


Figure 10. Relation of the mixed signal azimuth α to the difference between the phases φ for the various ratios of amplitude of both signals in case of directional fading.

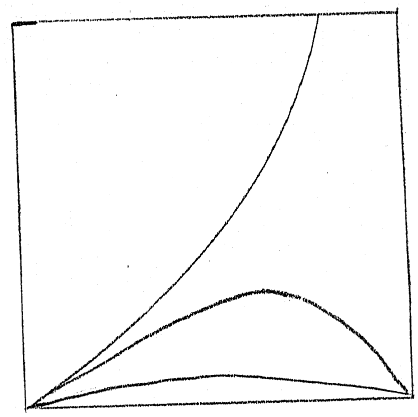


Figure 11. Relation of the ratio of ellipse half-axes of a mixed signal to the difference between phases φ.

Figure 9 shows a few results of such experiments. From the figure we see clearly that in the case where following the indicated method, we "eliminated" one of the impulses, the character of the amplitude fading of the single signal changed and, as a rule, became less deep. This result is very typical for the characteristic of the phenomena which we are studying here.

In order to form a conception of the relation between the character of directional fading and the ratio of common and uncommon signal amplitudes and of the differences between them, we made calculations the results of which are shown in Figures 10 and 11.

Let us suppose, as was done with the disposition of the transmitter in Moscow, that the angle between the arrival direction of the common and the uncommon signals is 53 degrees (see Table). In this case the mixed signal consists of two oscillations, one of which, $x_1 = \cos \omega t$ has a direction $\alpha_2 = 53$ degrees. The combination of x_1 and x_2 gives us an elliptical oscillation the main axis of which forms with the direction $\alpha_1 = 0$ an angle which can be determined from the formula

$$\tan 2\alpha = \frac{A^2 \sin 2\alpha_2 + 2A \cos \varphi \sin \alpha_2}{1 + A^2 \cos 2\alpha_2 + 2A \cos \varphi \cos \alpha_2}, \quad (4.1)$$

while the correlation between the ellipse half-axes is equal to

$$\frac{a_y^2}{a_x^2} = \frac{\{1+A^2+2A\cos\varphi\cos\alpha_2\}\cos 2\alpha - \{1+A^2\cos 2\alpha_2 + 2A\cos\varphi\cos\alpha_2\}}{\{1+A^2+2A\cos\varphi\cos\alpha_2\}\cos 2\alpha + \{1+A^2\cos 2\alpha_2 + 2A\cos\varphi\cos\alpha_2\}} . \quad (4\text{-}2)$$

From Figures 10 and 11, calculated according to formulas (4.1) and (4.2), we can clearly see the general character of the changes of mixed signal azimuth α and the degree of its elliptical condition characterizing the sharpness of the bearing minimum.

Relation Between the Azimuths of Common and Uncommon Signals and the Angle

After we had obtained the first results of our measurements of the arrival directions (bearing values) of various types of impulses, there arose the question about the possible physical nature of the phenomenon which we are here studying. It soon became clear that the anisotropy of the ionosphere was the cause of the observed effect. Naturally, the idea came up immediately how to set up an experiment that would solve the problem. Even before the calculations we understood that the direction of the magnetic vector of the earth H_o is the optical axis of ionosphere symmetry and that in relation to it the phenomenon had to be symmetrical and, when H_o lies on the plane of wave descent, the observed effect is supposed to disappear. Therefore, for the disposition of the transmitter we first chose a point situated approximately in the direction of the magnetic deflection in relation to the receiver. The experiments conducted showed that the effect disappears almost entirely (the angle between the directions of the common and the uncommon signals dropped from -53 degrees to -11 degrees. The data of the measurements were not totally understood at the time. However, a subsequent analysis of these data showed that during the experiments we failed almost completely to observe the above mentioned directional fading which, clearly, is a consequence of the effect of common and uncommon ray deflection from the plane of wave descent -- (from the true direction).

Later we made experiments with the transmitter situated in various places. Vast organizational difficulties arose ceaselessly and it was not always possible to conduct the experiments in the previously charted relative position of the transmitter and receiver which, for one reason or another seemed necessary.

The results of these experiments are offered in the Table and in Figure 12.

In order to check the dependability of the measurement results (we remind the reader that the calculations were carried out only at the end of the experiments, see [1]), we carried out many repeat measurements. The data offered in the Table and on Figure 12 are the result of averaging on the basis of a large number of measurements which, as we already mentioned before, had small discrepancies in the single measurements and certain oscillations provoked by the reflection from the ionosphere conditions.

[See following page for Table]

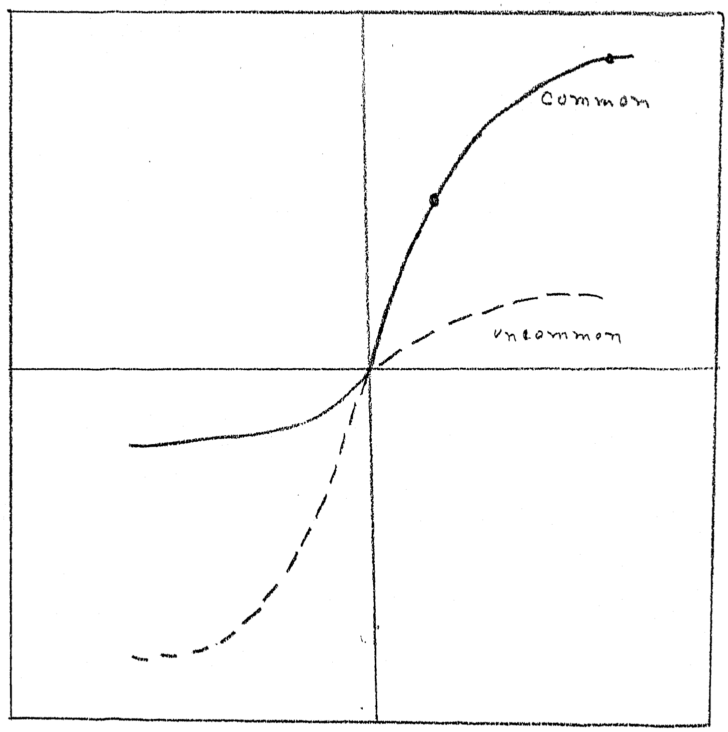


Figure 12. Relation between the angle α -- between the true direction and the actual direction of arrival to the receiving point of a common and an uncommon signal -- and the angle ψ_H.

TABLE

AVERAGE RESULTS OF THE MEASUREMENTS OF αe IN RELATION TO ψH

(Data of the earth magnetic field: horizontal component $H_1 = 0.172$ G; vertical component $Z_1 = 0.477$ G; inclination: $70^{\circ}12'$; deviation: $+7^{\circ}$ East.)

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Relative disposition of transmitting and receiving points		Average value of signal azimuth		Frequency Diapason in MH_z	Time of Observations	Common Signal In degrees	Uncommon Signal In degrees	ψH in degrees
Distance in Kms.	Meaning of Geographical Azimuth of Transmitting pt. In degrees	Common	Uncommon					
45	7	7	356	$5.5 \div 7$	July 1947	0	-11	-1
38	26	27	333	$2 \div 11$	All year (1945 - 1947)	+1	-53	-19
56	28	26	332	$5.5 \div 8$	June 1947	-2	-56	-21
58	47	30	340	$5.0 \div 5.5$	June 1947	-17	-67	-40
42	61	42	347	$5.5 \div 10$	Oct. 1947	-19	-74	-54
41	347	28	343	$5.5 \div 7$	July 1947	+41	+ 4	+20
41	309	23	329	$5.5 \div 8.1$	Sept.1947	+74	+20	+58

Figure 12 shows the relation between the angle α_e -- between the true direction (observation point azimuth) and the direction of arrival to the receiving point of a common and an uncommon signal -- and the angle ψ_H -- between the true direction and the horizontal component H_o of the earth magnetic field. The choice of the angulation sign is explained in Figure 13 and 14 (see below).

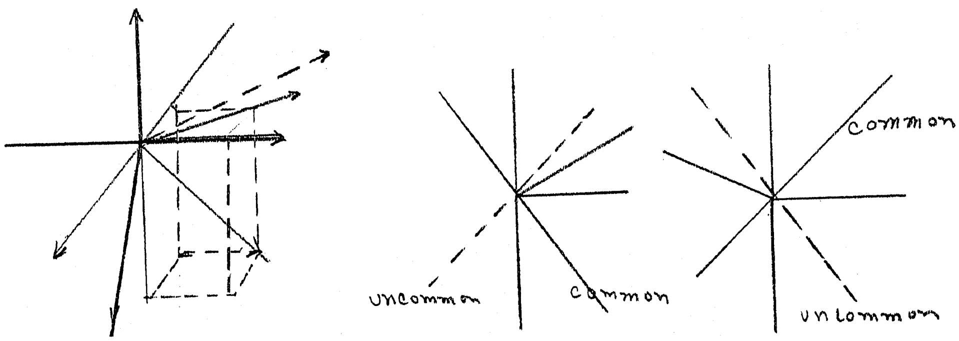


Figure 13

From the table and Figure 12 we get a general idea of the relation between

A comparison of these data with the results of theoretical calculations (see [1], Figure 23) shows the following:

(1) The general character of the phenomenon under real conditions is in good accord with theory.

The coincidence of experimental and theoretical data is expressed in a good agreement of the sign and of general character of the effect. It is significant that both in the experiment and in theory α_e passes 0 when $\varphi_H = 0$

(2) A divergence between experiment and theory appears in a quantitative disparity. Also, experimentally, we observe a certain asymmetry in the progress of ϕ_e for the common and the uncommon signals during passage over zero.

Possibly, this divergence between experiment and theory may be explained by part or all the conditions enumerated below.

(1) The theory was created only for a layer non-homogeneous in its thickness. Also, we are discussing a linear layer. We already noted above that for a parabolic or for any simple layer the character of the phenomena will be one and the same. However, if we suppose that in the central part of the layer, i.e. in the region of uncommon wave reflection (where the wave group retardation time changes considerably and where it has a significant deflection from the plane of descent), there occurs a slowed-down change of the ionization in relation to the altitude, then considerably qualitative divergences from theory and an asymmetric state in the progress of the rays may appear.

(2) In the calculations we do not take into consideration the non-homogeneousness of the layer along the X, Y axes -- in horizontal directions. At the same time, from many data it follows that the F layer often has a "cloudy" structure and other non-homogeneous effects.

(3) The theory says, as usual, that the earth magnetic field is homogeneous, that is, that the vector H_0 remains constant everywhere. In practice, however, it is well known that the lines of equal magnetic deviation on the surface of the earth are not circumferences, but lines of changing curvature. It is totally

unknown from the experimental data how the vector of the earth magnetic field changes its position in the ionosphere, above the surface of the earth.

Even from an examination of the graphs of the theoretical calculation (One should bear in mind that in a magnetically active medium the principle of magnetic reciprocity is not observed.) it is easy to understand that one may expect various complications of the ray progress in the ionosphere.

Estimate of the Polarization Structure of the Field at the Receiving Point

It is interesting to observe how the polarization structure of the field at the receiving point changed under our experimental conditions. By comparing it with the results of measurements one may clarify whether or not the horizontal revolving (elliptically built) field of the received wave had any substantial influence on these measurements (admitting that this field was received through the horizontal parts (feeders) of the antenna.

From formula (3.6) [1] we may say that when the wave leaves the ionosphere, i.e. when $v \to 0$, the relation between the half-axes of the ellipse of each wave in the plane and the perpendicular normal to the wave front N is equal to

$$\frac{E_{x_1}}{E_{y_1}} = i\,\frac{2h_L}{h_T^2 \pm \sqrt{h_T^4 + 4h_L^2}} \qquad (4.3)$$

where X_1 is the direction of the axis chosen in the plane, normal to the wave front, so that it lays in the same plane as H_o and N (see Figure 13). Thus, the transversal component H_T of the magnetic

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field H_o is directed along the axis X_1. The longitudinal component is directed along N. The axis Y_1 (which is not shown on Figure 13) is perpendicular to the plane ($H_o N$) and to X_1. In the formula (4.3)

$$h_L = \frac{e|H_o|}{mc\omega} \cos (H_o N), \; h_T = \frac{e|H_o|}{mc\omega} \sin (H_o N). \quad (4.4)$$

From (4.3) we see that the main axes of the ellipses are disposed along X_1, Y_1, and the minor half-axis of the common wave ellipse is directed along the axis Y_1, while that of the uncommon wave is directed along the axis X_1.

The position of the ellipses on the horizontal plane (on the surface of the earth) in relation to ψ_H and the angle χ_o -- exit of the wave front from the layer -- may be calculated if we project the ellipses (4.3) onto the plane XY. For this we must determine, in relation to these wuantities, the values of the angular coefficients of the unit vector $X_1 = H_T(\alpha_T, \beta_T, \gamma_T)$,

$$\begin{vmatrix} \alpha_T & \beta_T & \gamma_T \\ \alpha_H & \beta_H & \gamma_H \\ \sin\chi_o & 0 & \cos\chi_o \end{vmatrix} = 0 \quad (4.5)$$

and of two other simple correlations

$$\alpha_T^2 + \beta_T^2 + \gamma_T^2 = 1$$

and (4.6)

$$\left.\alpha_T \alpha_H + \beta_T \beta_H + \gamma_T \gamma_H = \sqrt{1 - (\alpha_H \sin\chi_o + \gamma_H \cos\chi_o)^2}\right\}.$$

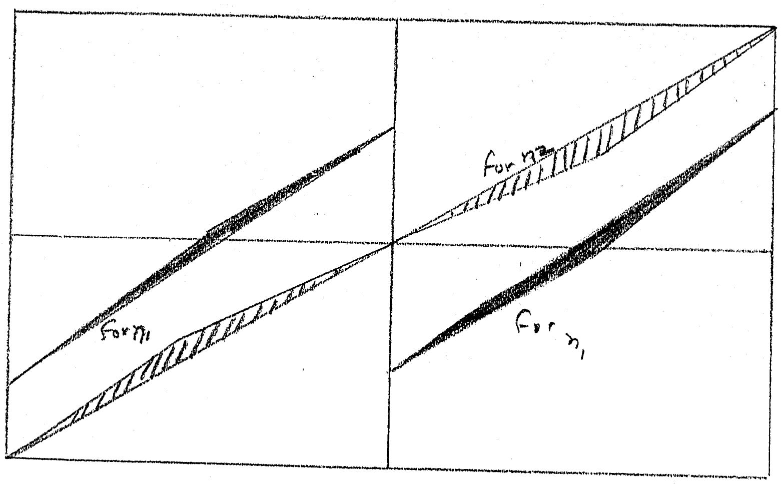

Figure 15. Results of calculation of the relati n between $\alpha\ p$ -- angle between the true direction and the minor half-axis of the ellipse and ψ_H , respectively for common and uncommon waves with values $\chi_0 = 0 \div 11$ degrees

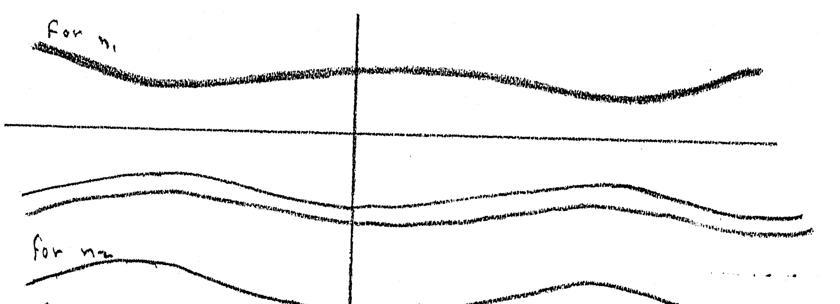

Figure 16. Relation between the ellipse half-axes ratio and the value of the angle ψ_H for common and uncommon waves with values $\chi_0 = 0 \div 11°$

Figure 15 shows the results of the calculation of α_P -- angle between the true direction X axis lying on the plane of descent and the direction of the minor half-axis of the ellipse -- in relation to ψ_H respectively for the common (n_1) and the uncommon (n_2) waves and for values $\chi_0 = 0 \div 11°$

Figure 14 shows the accepted condition for angulation. Figure 16 shows the change of relation between the ellipse half-axes in those cases, and ψ_H.

From Figure 15 we see (The jump of n_1 at the point $\psi_H = 0$ has a conventional character and is explained by the fact that the determination of the ellipse half-axis direction has a meaning only in two quarters of the quadrant] that the change of α_P -- positions of the minor half-axis of the ellipses of various signals with bearing on a minimum -- has a totally different character than the experimentally obtained progress of α_e shown on Figure 12. The fact that with $\psi_H = 0$ the value of α_e equals zero for one signal and -90 degrees for the other is one very important difference between Figure 15 and Figure 12.

Further, it follows from Figure 16 that under our experimental conditions the ellipses of the horizontal components of the electromagnetic field have a shape close to a circumference and the determination of their orientation at the receiving point on the surface of the earth is impossible in practice because of the diffusion of their minimum. In practice one observes almost full minimums of the common and the uncommon signals.

We also examine the character of the total effect from the horizontal and vertical components of the field. In this case, as is easily shown, the electromotive force values in the two reciprocally crossed coils of the goniometer -- which create the revolving field -- are proportional

$$\left.\begin{aligned} E_y &= A_y^{(0)} \cos \omega t + a \cos \alpha \sin(\omega t - \varphi), \\ E_x &= A_x^{(0)} \sin \omega t + a \sin \alpha \sin(\omega t - \varphi) \end{aligned}\right\} \qquad (4.7)$$

for a common wave, and

$$\left.\begin{aligned} E_y &= A_y^{(x)} \sin \omega t - a \cos \alpha \cos(\omega t - \varphi), \\ E_x &= A_x^{(x)} \cos \omega t - a \sin \alpha \sin(\omega t - \varphi). \end{aligned}\right\} \qquad (4.8)$$

for an uncommon wave.

In the expressions (4.7) and (4.8) A_y and A_z are respectively the values of the electromotive force amplitudes induced from the horizontal elliptical field (the system of coordinates has been chosen along the main axes of the ellipse which form the filed in the plane XY), α is the angle between the arrival direction of the wave and the Y axis; a is the electromotive force amplitude induced from the vertical component of the field; and φ is the phase introduced by the antenna system.

From the expressions (4.7) and (4.8) we may derive formulas, analogous to formulas (4.1) and (4.2), which in the given case are more ponderous. And we may also calculate the change of the ellipse position and the ratio between its half-axis in relation to ψ_H (the angle between the signal arrival direction and the horizontal component of the earth magnetic field).

Figure 17 shows the family of curves which characterize the change of the angle α_ρ between the signal arrival direction and the minor half-axis of the ellipse in relation to ψ_H for common and uncommon waves and respectively for various values of a. In the calculations we have taken into consideration the results deriving from (4.3) and giving us the position of the ellipse (Ay, Ax). One of the half-axes of the original ellipse (A_y, A_x) is assumed to be equal to one. Thus the quantity a characterizes the relation of the electromotive force amplitudes induced from the vertical and the horizontal components of the field (since in the given case the ellipse is close to a circumference).

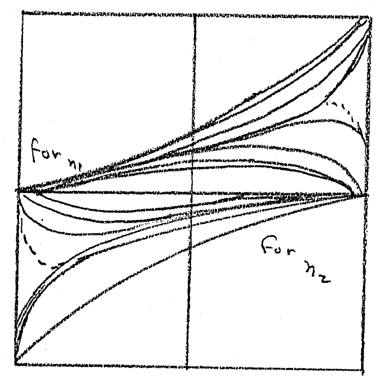

Figure 17. Family of curves for the relation between α_ρ -- angle between the true direction of the signal and the minor half-axis of the ellipse -- and the angle ψ_H for common and uncommon waves and respectively for various values of a.

Figure 17 shows only the results of calculations for $\varphi = 0$ since the character of the curves remains the same with other values of φ.

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From Figure 17 we see that the progress of the relation between α_P and ψ_H differs rather substantially from the progress of α_L (Figure 12). We must bear in mind that with low values of a (order of 2 ÷ 3) the relation between the poles of the ellipse (we do not give these graphs) is rather high ($\sim$0.2 - 0.5). This means that the total effect is characterized by a diffused bearing.

Our calculations also show that the horizontal components of the field at the receiving point, apparently did not have a substantial influence on the results of measurements because otherwise the character of the experimental curve would have been different. Generally speaking one could isolate the effect searched for in its pure aspect by way of calculations.

5. Fundamental Conclusions

In the preceding sections we have described the results of the experimental exploration of the ionosphere and also the methodology and the equipment with whose help it was conducted. We studied the direction of the arrival to the receiving point of impulses reflected from the ionosphere, both in the case of a single reflected signal and in the case of the presence of a doublet of signals resulting from the double ray refraction in the ionosphere. We compared the experimental data with the results of the calculation of the ray trajectory in a magnetically active medium -- ionosphere [1].

The completed work allows us to make certain new conclusions.

(1) Thanks to the anisotropy of the ionosphere, pro-

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voked by the external magnetic field of the earth, two signals, resulting from the splitting of the impulse falling onto the ionosphere, propagate along various trajectories which lead them out of the plane of descent. Because of this, each of them comes to the receiving point from various directions, differing from the true direction between the receiving point and the radiator.

(2) The arrival direction of the so-called common and uncommon signals have fully determined values for the given reciprocal position of the transmitting and the receiving devices.

Individual measurements of the signal bearing give a deep, stable minimum. However one observes certain oscillations of separate measurements around an average value which is constant. Apparently these oscillations are provoked by the non-homogeneous character of the ionosphere in its horizontal direction.

(3) The angle α_{ℓ} between the true direction -- the line connecting the receiving and radiating points -- and the arrival directions of the common and the uncommon signals depends on the orientation in relation to the true direction of the horizontal component of the magnetic vector of the earth H_o. When H_o lies on the plane of wave descent, the value of α_{ℓ} is equal to zero for both signals.

(4) The single reflected impulse more often than not has an unstable bearing value so that the bearing constantly is completely diffused or rotates. In these cases we meet with interference between two signals arriving from different directions. We then observe the so-called directional fading of a "mixed" signal.

This type of fading often provokes in practice an unstable and incorrect functioning of the direction finders, the reason for which lies not in the equipment, but in the nature of physical phenomena, i.e. is determined not by a polarization error of the direction finder, but by a change in the direction of arrival of the wave to the receiving point.

(5) The experimental data are in good accord with the results of calculations. However there still is a quantitative divergence and a difference in a number of details between the experimental and calculation data. The basic reason for these differences lie apparently in the fact that theory does not take into consideration the non-homogeneousness of the ionosphere in the horizontal directions and the changes in orientation of the vector of the magnetic field of the earth. These peculiarities of the ionosphere may not be taken into consideration not only because of the tremendous complexity of the calculations, but especially because of the lack of any experimental data. These peculiarities of the ionosphere, generally speaking, must be rather inconstant because of their complex geophysical nature.

(6) The study of the observed effect unveiled new possibilities of applied methodology for the experimental exploration of the ionosphere. Together with a space selection of the received signals, the devices also allow to make their phase selection.

Thanks to the difference between the arrival directions of the common and the uncommon signals, one may fairly easily and surely differentiate the signals received, i.e. determine their polarization type. This is very important in the field of physical exploration of the ionosphere. Thanks to this for example we see from the experiments made that in the reflections from the E layer we get common and uncommon signals. Besides, we also explores the nature of each of the signals in triplets and quadruplets, [4]. This property of the methodology may also be used for a detailed study of the selective absorption in the ionosphere and for the solution of other problems as well.

(7) The data obtained show the necessity of taking into consideration the studied effect during direction finding. The corresponding calculations, and also a fairly complete series of experiments will allow to draw error charts for the practice of direction finding. These charts will indicate the errors provoked by the anisotropy effect of the ionosphere.

In conclusion I can only remember with deep gratitude Academician N. D. Papaleksi who showed great interest in this work. In part the work was done while he was still alive and he gave us full cooperation and a series of valuable advice and directions.

I express my sincere appreciation to Doctor of physical-mathematical sciences V. L. Ginsburg for the discussion of this work and his valuable advice and comments. I am also grateful to Junior Scientific Collaborator A. A. Aynberg, Senior Radio Technician I. B. Dokhnovskiy and to the VVA Assistant A. A. Tankov for their help during this work.

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